BATTERY MODULE AND PACK ASSEMBLY PROCESS
PEM of RWTH Aachen University has been active for many years in the area of lithium-ion battery production. The range of activities covers automotive as well as stationary applications. Many national and international industry projects with companies throughout the entire value chain as well as leading positions in notable research projects allow PEM to offer a broad expertise.

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The German Mechanical Engineering Industry Association (VDMA) represents more than 3200 companies in the mechanical engineering sector, which is dominated by SMEs. The battery production department focuses on battery production technology. Member companies supply machines, plants, machine components, tools and services in the entire process chain of battery production: From raw material preparation, electrode production and cell assembly to module and pack production.

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Based on the brochure “Lithium-ion battery cell production process”, this brochure schematically illustrates the further processing of the cell into battery modules and finally into a battery pack.

The individual cells are connected serial or in parallel in modules. Several modules as well as further electrical, mechanical and thermal components are assembled to a pack.

Each pack has a different Layout depending on the required performance. Due to the large number of different product and process variants, common information on the process parameters cannot be stated and can be specified in more detail in a joint discussion with the PEM Chair or the VDMA.

**Technological Development**

of battery modules and battery packs

<table>
<thead>
<tr>
<th>Product innovation (excerpt)</th>
<th>Process innovation (excerpt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Integration</strong></td>
<td><strong>Module assembly</strong></td>
</tr>
<tr>
<td>• Simplification of the module housing</td>
<td></td>
</tr>
<tr>
<td>• Pack housing plastic construction</td>
<td></td>
</tr>
<tr>
<td><strong>Electrical Integration</strong></td>
<td>• Elimination of cell gluing process</td>
</tr>
<tr>
<td>• Relocating of the BMS</td>
<td>• Elimination of module assembly</td>
</tr>
<tr>
<td>• Contacting system</td>
<td><strong>Pack assembly</strong></td>
</tr>
<tr>
<td></td>
<td>• Assembly low voltage area</td>
</tr>
<tr>
<td></td>
<td>• Joining pack cover</td>
</tr>
</tbody>
</table>

- Todays technology developments will improve the mechanical and electrical integration of the housings and the overall systems.
- The Research on product and process innovations is primarily aiming at reducing costs and simplifying the assembly.
Overview
Comparison of battery modules

Pouch cell battery module

- It is important to note that the pouch cells expand/shrink in its thickness during the charging or discharging cycle.
- Each pouch cell is inserted into a frame.
- Due to the swelling of the cells, the frames are arrested flexible by springs.
- Cooling in a pouch module is optional and can be served by either convective or liquid coolant.
- For example, pouch cells can be serial connected and cooled via U-profiles.

Pouch cell battery module

- In the architecture of a round cell module, the cells are fixed by the module case.
- The space between the cells can be used by a cooling system or direct cooling.
- The metal housing prevents the cell from swelling.
- At module level, the cells can be connected both serial and parallel.
- The cells are contacted via a metal plate on both sides.

Prismatic cell battery module

- Prismatic cells can be installed without remaining gaps.
- The individual cells are glued together.
- The adhesive film serves both as electrical and thermal insulator in the event of an accident.
- The cells are clamped with a bandage and/or a plastic or metal housing.
Exact positioning and secure fixation of the cells to each other is necessary.

Power, charging time and service life depending on the weakest cell.

Speed of the process strongly depends on the degree of automation.

Delivery quality of the supplier determines the amount of inspection.

Precise handling of the cells.

Adjusted contact pressure during transport and insertion to prevent electrolyte leakage.

- Goods in (using prismatic cells as an example): Scanning of the product labels and sorting according to the performance data.
- Receiving inspection to sort out faulty cells (electrochemical impedance analysis, voltage measurement, capacity analysis, etc.).
- Depending on delivery condition, cleaning and/or activating of the surfaces.
- Joining of the cells (e.g. using liquid or solid adhesives).
- The joining medium must be electrically insulating to prevent from internal short circuits. Polyurethane-based adhesives with elastomeric properties after curing are in common use.
- The cells are stacked in a defined way.
- Depending on the joining medium, extraction of solvent vapours.

Process parameters & requirements
- Exact positioning and secure fixation of the cells to each other is necessary
- Power, charging time and service life depending on the weakest cell
- Speed of the process strongly depends on the degree of automation
- Delivery quality of the supplier determines the amount of inspection

Technology alternatives [excerpt]
- Glue gun for glue application
- Application of double-sided adhesive tapes

Quality influences [excerpt]
- Position-accurate cell handling
- Bonding and pressing method

Quality features [excerpt]
- Precise handling of the cells
- Adjusted contact pressure during transport and insertion to prevent electrolyte leakage

Production costs* [excerpt]
Invest for machinery and equipment: € 4.0-5.0 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Insulation and Tensioning
Module production

- Stacked cells are pressed to create a defined stack geometry and minimize swelling during charge and discharge.
- The pressure is applied onto the stack by a clamping device, a bandage or by the module body itself.
- Plastic plates or foils are used for heat dissipation and electrical insulation, which prevent heat transfer and current flow between the cells. These are intended to interrupt a chain reaction in the event of a cell failure.
- Exact positioning of the components on the module and subsequent gluing and/or screwing and insertion into the housing.
- For pouch cells, instead of gluing, it is possible to insert them into individual frames (drawer systems) and then bracing them.

Process parameters & requirements
- Max. compression forces in N and N/cm² (depending on cell type and specifications)
- Uniform contact pressure between insulation plate and module in N/cm²
- Fast process execution and curing times for potting compounds
- Tightening torques of the connecting elements, tensions

Technology alternatives [excerpt]
- Automatic grippers for cell stacking
- Manually filled cell magazines for feeding the cells for module assembly

Quality influences [excerpt]
- Precise handling technology
- Precise pressing

Quality features [excerpt]
- Precise positioning measures
- Optimal heat dissipation
- Consideration of the tolerance chains of cells and module components

Production costs* [excerpt]
Invest for machinery and equipment: € 1.0-1.5 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
### Electrical Contacting

**Module production**

<table>
<thead>
<tr>
<th>Laser</th>
<th>Ultrasonic</th>
<th>Current</th>
<th>Screws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast / Efficient</td>
<td>Gentle</td>
<td>Low investment</td>
<td>Detachable connection</td>
</tr>
<tr>
<td>High heat input</td>
<td>expenses</td>
<td>Material dependent</td>
<td>Contact resistance</td>
</tr>
</tbody>
</table>

- Wiring of the cells by electrical connection of the contact tabs / current collectors. Depending on the module voltage, the cells are contacted to form one or more parallel strings.
- Contact e.g. by the use of ultrasonic welding (low heat input), laser welding (high precision) or screw connections (electrical losses due to contact resistances).
- Checking the joints for conductivity by resistance measurements.
- With a high degree of automation, the welding seams can be inspected during the welding process by an optical inspection.

### Process parameters & requirements
- Seams must be free of dust and grease and have low reflections for laser welding.
- Ultrasonic welding: frequency: 20-40 kHz, amplitude: 10-50 μm, pressure: 1-10 MPa
- Laser welding: 1000-4000 W
- Low heat input into the cell

### Technology alternatives [excerpt]
- Laser welding
- Ultrasonic welding
- Screwing

### Quality influences [excerpt]
- Joining Technology / Welding Technology
- Monitoring and testing technology
- Positioning accuracy of the clamping device.

### Quality features [excerpt]
- Large joining area to minimize electrical resistance
- Cleanliness of the joints
- Low thermal load

### Production costs* [excerpt]
Invest for machinery and equipment: € 10.5-11.0 million

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*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Comparison of Welding Processes
Module production

Laser welding
- A laser optic or a diode laser heats the current collector and the contact plate until they are fused.
- This process takes less than a second due to the fast energy supply.
- The space requirement of a laser system is low.
- Laser welding offers a high degree of flexibility for subsequent process adaptation, as it is a contactless process.

Ultrasonic welding
- The necessary heat of fusion is generated by interfacial friction and acoustic absorption.
- The subsequent cooling creates a homogeneous connection.
- Advantageous when welding the same materials.
- The very high joining precision and the accessibility of the contact surfaces for the less flexible sonotrode with counterholder are limiting factors.

Resistance welding
- In resistance welding, the welding heat is generated by an electrical resistance.
- Two opposite welding electrodes are required for the welding process.
- The suitability of the materials depends on the thermal conductivity and the melting point.
Mounting of the Slave Circuit Board
Module production

- Positioning the slave circuit board of the battery management system (BMS) or a complete contacting unit for processing the data and controlling the sensors.
- Joining the circuit board to the module by welding and/or screwing.
- Mounting of the voltage measuring cables by means of screwed or welded connections and gluing of the temperature sensors.
- Connection of the sensor system to the circuit board via plug connections.
- Functional test by signal testing and random testing of the weld seams by X-ray or ultrasonic measurement.

Process parameters & requirements
- Damage-free joining of circuit board and sensors
- Delivery of the parts with defined surface tensions
- Precise installation and handling of the highly sensitive sensors
- Low heat input (fire hazard)

Technology alternatives [excerpt]
- Laser welding
- Screwing
- Plug-in connection

Quality influences [excerpt]
- Precision of welding technology
- Selected assembly technology
- Exact positioning

Quality features [excerpt]
- Exact positioning of sensors and circuit board (risk of short circuits)
- Quality of the joints
- High sensitivity of cell & sensors

Production costs* [excerpt]
Invest for machinery and equipment: € 0.6-0.8 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Mounting of the housing cover

Module production

- Attaching and fitting cables (power & COM cables).
- Wiring the controller and, if necessary, the cooling system for later connection to the BMS master.
- Mounting of the lit, fixing with screws or clips.
- Testing the module:
  - External irregularities (optical tolerances)
  - Functionality of communication and sensors (software test)
  - Cell voltage, cell difference (balancing)
  - State of Charge (SOC) of the module
  - HV strength (resistance measurement)
  - If necessary, tightness of the cooling circuit and the module (e.g. gas leakage test, overpressure test, vacuum test)
- Protective caps, label application and preparation for transport.

Process parameters & requirements

- Handling and safety regulations for employee controls
- Installation of the flexible cable harnesses
- Ensuring transport safety (cables, connections, protective caps, etc.)

Technology alternatives [excerpt]

- Screw driving robot with magazine
- Clipping of the module cover by plug connectors

Quality influences [excerpt]

- Assembly technology depending on the module concept
- Measuring and testing technology

Quality features [excerpt]

- Exterior integrity and technical cleanliness
- Permitted amount of rework
- Transportability (cables, connections)

Production costs* [excerpt]

Invest for machinery and equipment: € 0.2-0.4 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Module production

- Mount the cooling plates in the bottom of the battery pack tray for cooling the modules during operation (if necessary also heating function).
- Insert the battery modules into the pack housing by means of appropriate grippers into the bottom of the pack.
- Repeat these steps until all modules (here schematically three modules per pack) are inserted.
- The construction and wiring of battery packs vary greatly between applications and suppliers (e.g. 4S3P, 6S3P, 12S1P etc. / S=Serial, P=Parallel).
- Two serial module strings are often connected in parallel.
- Fully electric vehicles have high-energy cells. Hybrid vehicles have high-power cells.

Process parameters & requirements
- Protective equipment and high-voltage safety training required
- Module connections must be securely positioned and must not interfere with the assembly process.
- Handling of the partly very large radiator elements by employees (occupational health and safety)

Technology alternatives [excerpt]
- Fully automated gripper assembly
- Semi-automatic insertion of modules with manipulators

Quality influences [excerpt]
- Flexible assembly technology for different storage geometries

Quality features [excerpt]
- Danger of short circuits in module handling
- Damage-free transport due to adapted contact pressure
- Handling of large housings and coolers

Production costs* [excerpt]
Investment for machinery: approx. 1.0 million €

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Attachment of the Modules

Pack production

- Fixing the battery modules, e.g. by means of screw connections, in the places provided in the battery pack housing.
- The additional screw connection can increase the rigidity and additionally protects against vibrations during operation.
- Ensure the correct position and damage-free installation using suitable systems (e.g. camera, mounting aids, centering pins, etc.).
- Typical screw sizes depending on structure M6-M12.
- Rotation prevention when tightening the screws must be ensured.

Process parameters & requirements
- Precise and damage-free fixing of the modules to the floor
- Fixing by gluing, plugging or screwing the components together
- Connection to cooler structures
- Tightening torques of the screws according to module size and screw type

Technology alternatives [excerpt]
- No alternatives available for large series production

Quality influences [excerpt]
- Integration of supporting assembly aids (e.g. joining cone in packing body)
- Automation of a flexible production line

Quality features [excerpt]
- Guaranteed tight fit of the modules
- Design of the overall system for possible tolerance variation
- Contact surfaces for heat dissipation

Production costs* [excerpt]
Invest for machinery and equipment: € 0.9-1.2 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Electrical & Thermal Integration
Pack production

- Positioning of the cooling system in the holder provided and connecting it to cooling elements in the pack housing.
- Mounting of the high-voltage module consisting of relay, fuses, pre-charge & current measuring system, insulation monitoring etc.
- Connecting of HV and LV wiring harness to modules and peripherals.
- Installation and wiring of the battery management system (BMS Master) to control the cooling system, modules, slave circuit boards and high-voltage module.
- Installation by specially trained employees if the voltage is above 60 V (work under voltage, sensitization for battery risk - electrician).
- Connect connections, valves and plugs on the outer housing as preparation for vehicle integration.

Process parameters & requirements
- Cooling system, battery management system, high-voltage module are usually pre-assembled brought-in parts.
- Assembly of the flexible cables can only be carried out by a trained employee and is difficult to automate.

Technology alternatives [excerpt]
- Busbar systems for simultaneous contacting and fixing of the modules

Quality influences [excerpt]
- Assembly technology and support
- Poka-Yoke design for protection against false assembly/mounting

Quality features [excerpt]
- Correct positioning and wiring of peripheral devices
- Accessibility of connection points
- High-voltage safety (> 60 V) for employees

Production costs* [excerpt]
Invest for machinery and equipment: € 0.9-1.0 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
• Apply the seals (e.g. rubber seal, sprayed or glued seals) to the edge of the housing or cover.
• Place the upper part of the housing or the cover and connect it (e.g. by screwing) to the battery pack housing.
• Check the housing for leaks by opening the bursting disc or using a leak tester.
• If necessary, check the tightness of the cooling circuit using suitable gas (e.g. helium) or leak detectors.
• Install a bursting disc in the battery pack housing to secure the pressure of the battery pack and ensure safety during operation.

Process parameters & requirements
• Dust tightness and resistance
• Seal must be suitable for temperature changes
• During the test, the housing may burst in the event of overpressure.
• Bursting disc necessary for safety protection during battery operation

Technology alternatives [excerpt]
• Check the components to ensure the final tightness.
• No complete alternative available in large series production

Quality influences [excerpt]
• Flexible assembly technology
• Leak test

Quality features [excerpt]
• Ensure tightness of the pack despite ventilation
• Definition of permitted reworking
• Service capability for opening the housing

Production costs* [excerpt]
Invest for machinery and equipment: € 1.8-2.0 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
Charging & Flashing
Pack production

Tasks

- Establish state of charge
- Functional test of thermal management

Module production

- Connect the BMS to a computer and flash with the latest software through a system analysis program.
- Check the correct functioning of all systems using the analysis program.
- Establish the desired consistent state of charge of all cells.
- If necessary, monitoring of the welded joints and the thermal management functions during operation by means of a thermographic measuring system.

Process parameters & requirements

- Installation of the latest software for battery management systems for corresponding vehicle variants (variant creation via software versions)
- Stick to functional tolerances
- Prevention of gas formation or ignition during the charging process due to negative pressure and housing

Technology alternatives [excerpt]

- No alternatives available for large series production

Quality influences [excerpt]

- battery management software
- Measuring and testing technology

Quality features [excerpt]

- Functionality of all components
- Heat development during charging process
- Protection against errors from previous production steps

Production costs* [excerpt]

Invest for machinery and equipment: € 3.8-4.0 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
End of Line

Pack production

- Connect the test devices to the respective cable connections or lines.
- Inspection of the entire electronics by test software and optical inspection by an employee.
- Testing the functionality of the BMS and its subcomponents (temperature sensors, slave circuit board, etc.).
- Charging/discharging the battery according to a defined performance profile and establishing a desired state of charge (SOC) for storage or vehicle assembly.
- Apply labels and warnings and mark as "tested" and release the pack.
- Packaging and transporting the battery pack.

Process parameters & requirements
- Final process with subsequent storage in workpiece carriers
- Catalogue of criteria for comprehensive testing (no uniform regulation)
- Good employee training necessary
- Defined delivery condition in coordination with vehicle assembly (holder, connections, software versions, etc.)

Technology alternatives [excerpt]
- Upstream balancing of the modules in incoming goods department or in holding positions within the production line

Quality influences [excerpt]
- Choice of measurement and test technology

Quality features [excerpt]
- Fulfilment of all quality features
- Definition of permitted rework
- Danger due to high voltage (> 60 V) for employees

Production costs* [excerpt]
Invest for machinery and equipment: € 3.0-3.2 million

*PEM study by RWTH Aachen University: Capacity of the pack: 150 Ah, pack voltage: 400 V, production capacity: 4 GWh/a
A high-voltage system and high-performance electronics for motor control are required to ensure operation of the charge control system.

The use of high-voltage technology additionally increases the safety requirements, especially in the event of crashes.

Since the connections for to the vehicle wiring harness are flexible, the process can hardly be automated and must be carried out by an employee with assembly aids.

The mechanical connection of the battery pack is made e.g. by mountings in the base module and corresponding screw connections (M10-M14).

Mountings are used to mount the same accumulators in different vehicle derivatives.

**Process parameters & requirements**
- Production line must be adapted to the needs of electric vehicles
- High battery weight requires modified front/rear module design. Purpose-Design vs. Conversion Design (conversion of combustion vehicles)
- Adaptation of test & maintenance techniques (e.g. to power supply with 400V)

**Technology alternatives [excerpt]**
- No alternatives available for large series production

**Quality influences [excerpt]**
- Production of electric vehicles on old production lines vs. production on specially adapted production lines

**Quality features [excerpt]**
- Assembly processes for batteries and cables
- Accessibility of cables and connections
- Serviceability of the components (disassembly, interchangeability, etc.)
Batteries can only be used economically for electric cars up to approx. 80% of their capacity (wear is not linear and strongly dependent on environment and use).

Decision for type of further use depending on performance data.

Second use:

- Further use in other areas (e.g. stationary energy storage for solar systems) with adapted control units.

Remanufacturing:

- Preparation for further use of individual components.

Recycling of cells:

- Sorting of batteries by type and removal of peripherals.
- Mechanical preparation (crushing under protective gas) and/or pyrolysis (strong heating) for "deactivation of the cells".
- Recycling by means of hydro- or pyrometallurgical processes and recovery of raw materials (especially nickel, cobalt, aluminium and copper).
- Minimum recycling efficiency: 50% of the average battery scrap mass.

Potentials [excerpt]

- No distinct recycling infrastructure established yet
- Recycling can counteract price fluctuations and dependencies for raw materials
- Simultaneous recycling of secondary batteries from the entertainment industry
- In particular, the recycling of cobalt, copper and nickel is already proving economically viable.

I. Sample process*

- Cells are melted down in a pyrometallurgical furnace
- Burn lithium, aluminum, electrolyte, separator and graphite & accumulate in the slag or leave process with exhaust gas
- Slag is made available to the construction industry
- The Co,Ni,Cu,Fe alloy produced during melting is granulated and hydro-metallurgically processed.

II. Example process*

- Cryogenic decomposition of lithium batteries
- Cooling by liquid nitrogen to approx. -196°C to reduce reactivity
- Battery cell shredding and shearing
- Reaction with sodium hydroxide (NaOH) and burning of the released hydrogen at the surface
- Lithium and lithium salts are precipitated & removed in solution in a targeted manner

*Source: F. Treffer: Lithium-ion battery recycling in R. Korthauer (Hrsg.), Lithium-Ion Batteries: Basics and Applications, Springer-Verlag 2018